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Integration of carbonation process with coal fired power plant to reduce CO_2 emissions

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Abstract

Global warming is a major issue for today's world due to continuous growth of greenhouse gas emissions. Carbon dioxide (CO_2) is the major greenhouse gas which occupies approximately 55% of the total greenhouse gases. Coal fired power plants are one of the major contributors of CO_2 emission. Different carbon capture and storage (CCS) technologies are available and some are being developed and implemented to minimise CO_2 emission. Mineral carbonation technology is one of the CCS technologies where CO_2 is sequestered as a solid environmentally safe stable carbonated product; however, carbonation process requires additional energy for pretreatment of the feed stocks (such as grinding of mineral) and compression of CO_2 before carbonation. The main advantage of this technology is its exothermic reaction process. Heat energy required for pretreatment can be supplied from this exothermic reaction if heat energy can be recovered. Sensible heat from carbonated product can also be recovered from the carbonation process. This paper presents the feasibility of integrating carbonation technology with coal fired power plant. The results of its impact on power plant efficiency are presented and analyzed through thermodynamic energy balance.

Key words: Global Warming; CCS; carbonation process; power plant; energy balance and efficiency

1. Introduction

The reduction of CO_2 emissions, particularly from coal-fired power plants, is arguably a key issue in today's world. Therefore study on how to reduce CO_2 emissions from a coal fired power plant is currently an important field of research. The main aim of this study is to work towards this issue. There are many CO_2 capture and sequestration (CCS) technologies available to mitigate CO_2 emissions to the atmosphere. Carbonation technology is one of the components of CCS technology where, gaseous CO_2 is converted into geologically stable carbonates. The first published study of CO_2 sequestration by Mineral Carbonation was in 1995 by Lackner [1]. The schematic drawing of a mineral CO_2 sequestration process reported by Kojima et al. [2] is shown in Figure 1.

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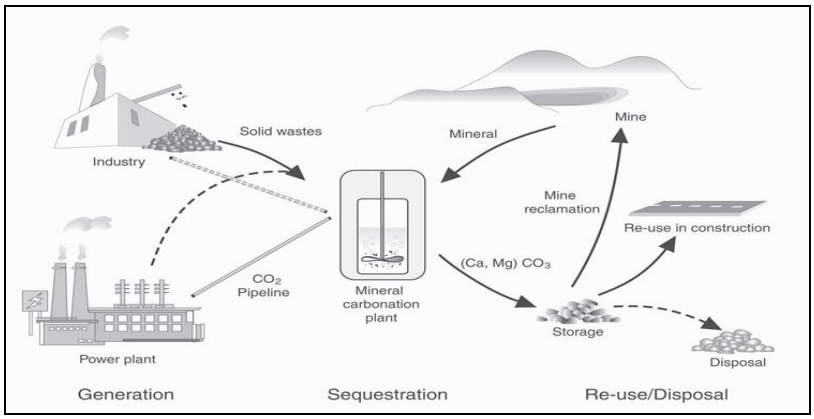

Fig. 1. Schematic drawing of a mineral CO_2 sequestration process, reported by Kojima et. al. [2]

This technology has some benefits over other CCS technologies because the carbonated products are environmentally safe and stable over geological time frames, raw materials are readily available, carbonated products are value added products and its main benefit is its exothermic reaction process. The general exothermic reaction involve in this process is shown below [3],

$$CaSiO_3\ (s)\ (wollastonite) + CO_2\ (g) \longrightarrow CaCO_3\ (s) + SiO_2\ (s) + \quad (Hr = -87\ kJ/mol)$$

This paper illustrates the feasibility of carbonation process into existing coal power plant to reduce CO_2 emissions. Energy flow model of aqueous carbonation process has been done for wollastonite feed stocks using Matlab/simulink software. Data used in this model was collected from previous studies and case study power plant.

Carbonation process initially requires heat energy supply from another source to heat the reactants up to the carbonation temperature. After completing one cycle of the carbonation reaction, significant exothermic energy from the reactor and sensible heat energy from the products can be recovered to continue the process. Electric energy for grinding and compression is needed to supply which is the main energy cost of carbonation process. It was estimated that 60% to 180% more energy could be required for carbonation process in a power plant with equivalent output without any carbon capture technology [4]. It can be noted that improvement of cost and energy associated with carbonation technology can be achieved through integration of exothermic energy and sensible heat energy of carbonation product if energy recovery option is available in the plant. Furthermore, surplus heat energy from carbonation process could be used to reduce the fuel energy consumption of power plant which will introduce less CO_2 emission from power generation process that has a great impact to reduce the global warming.

To meet the aim of this study a case study of carbonation process with a coal power plant equipped with different components namely, boiler, steam turbine, condenser, cooling tower, feed water heaters, feed pumps, generator and transformer was undertaken.

2. Case Study Coal Fired Power Plant

The reference power plant used in this study is a pulverized coal power plant with capacity of 1460 MW and the CO_2 emission without any CCS technology is 5,910,719 tons/year. Pulverised coal-fired power stations most commonly use the Rankine-based thermodynamic cycle. Figure 2, shows a simplified diagram of steam cycle equipped with reheating; and regenerative feed heating arrangement consisting of two feed heaters (HPH5 and HPH6) on HP side and three feed heaters (LPH1, LPH2 and LPH3) on LP side. Different subsystems mainly boiler and steam cycle subsystem are analysed based on the available thermodynamics properties, namely temperature (T), pressure (P), mass (m) and specific enthalpy (h) of different states of the Ranking cycle, then fuel efficiency performance is analysed with and without carbonation process. Matlab/simulink software was used for this analysis.

2.1. Steam Cycle Subsystem

Turbine: Steam at 16650 kPa and 538 ^oC is supplied to steam turbine from the boiler (steam generator). A small quantity of steam is bled off at 341.5 ^oC (4306 kPa) from HP turbine for feed heating and the remaining is reheated to 538 ^oC in a re-heater. Then the steam enters the IP turbine for further expansion. Small quantity of steam is bled off at 2237 kPa (456.1 ^oC) from the IP turbine for feed heating. The remaining steam expands to the LP turbine stage. Steam is bled off from LP turbine stage at 316 kPa (214.3 ^oC), 158 kPa (146.4 ^oC) and 73.2 kPa (91.1 ^oC). The remaining steam expands to the condenser pressure at 9.7 kPa. Work developed in the Turbine stages (High, intermediate and low pressure turbine) can be given by,

Work developed in the HP turbine stage

$$W_{HPT} = m_{10}\,(h_{10} - h_{13}) \tag{1}$$

Work developed in the IP turbine stage

$$W_{IPT} = m_{14}\,(h_{14} - h_{15}) + m_{17}\,(h_{15} - h_{17}) + m_{18}\,(h_{15} - h_{18}) \tag{2}$$

Work developed in the LP turbine stage

$$W_{LPT} = m_{18}\,(h_{18} - h_{19}) + m_{21}\,(h_{19} - h_{21}) + m_{23}\,(h_{19} - h_{23}) + m_{25}\,(h_{19} - h_{25}) \tag{3}$$

Condenser: At the condenser exit state 1 is saturated liquid at 45.8 ^OC and 9.7 kPa. In the condenser the vapour condenses and the temperature of the cooling water increases. The rate of heat transfer from the condensing steam to the cooling water per unit mass of working fluid passing through the condenser is given by,

$$Q_{CONDENSER} = m_{25}\,(h_{25} - h_1) \tag{4}$$

Pump: Work required by the pumps per unit of mass entering can be given by,

Work required by the Condensate Extraction Pump

$$W_{CEP} = m_1\,(h_2 - h_1) \tag{5}$$

Work required by the Boiler feed pump

$$W_{BFP} = m_6\,(h_7 - h_6) \tag{6}$$

2.2. Boiler Subsystem

Boiler losses were calculated based on the indirect method of heat losses, and then energy efficiency of boiler was calculated after determining all of the losses. Indirect method of boiler efficiency calculation is based on the *British Standard, BS 845:1987* and the *USA StandardASME PTC-4-1 Power Test Code Steam Generating Units*. In this method boiler efficiency is calculated by subtracting all heat losses from 100 [5]. Several thermodynamic parameters which include flue gas analysis, fuel analysis, flow rate, air analysis and temperature were collected from case study power plant and literature for boiler efficiency calculation. The total heat loss in the boiler was calculated as 11.13% which means the efficiency of the boiler in case study power plants was 88.87 %

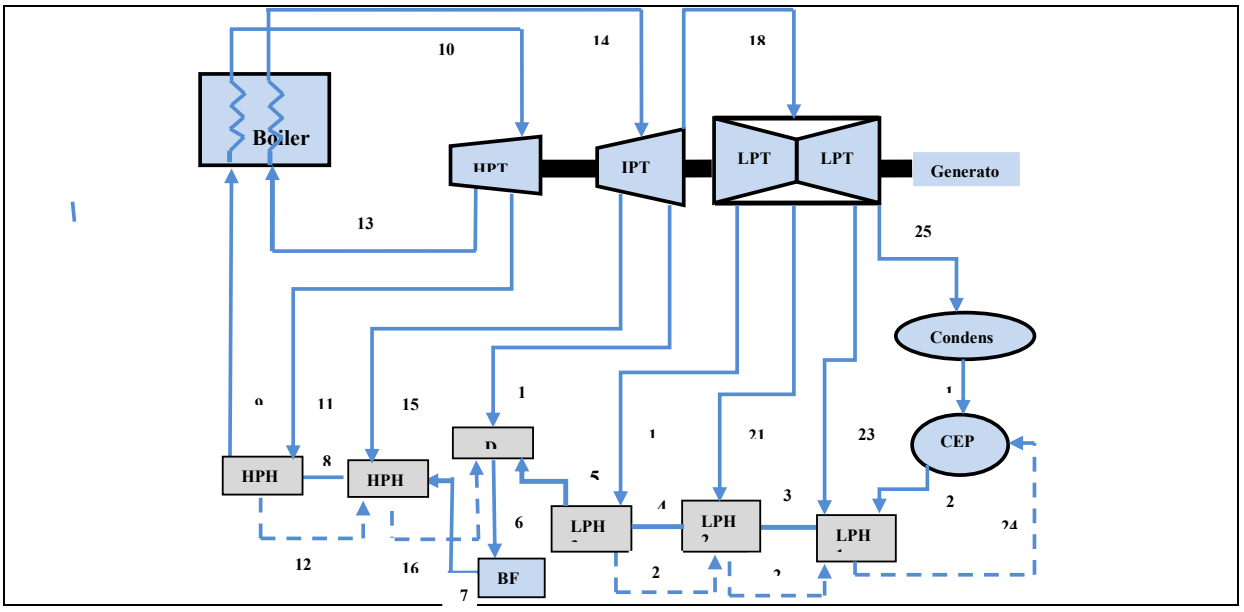

Fig. 2. Simplified diagram of Steam cycle of case study power plant [Note: HPT- high pressure turbine, IPT-Intermediate Pressure Turbine, LPT- Low pressure Turbine, HPH-High pressure feed water heater, LPH-Low pressure feed water heater, D- Dearetor, BFP- Boiler feed pump, CEP- Condensate Extraction Pump]

2.3. Fuel Energy Performance of Coal Power Plant

The energy or first law of efficiency (η) equation was used to calculate the fuel energy performance of coal power plant where η is defined as the ratio of energy output to the energy input to the system. The net electricity developed by the steam cycle was obtained by subtracting power plant's auxiliary electricity consumption from gross electricity developed by the steam cycle as electricity is needed to operate for power plant such as for lighting, pump, etc. The estimated net power developed by the cycle was 315.363 MW. The following equations [6] were used to calculate the fuel energy performance of power plant, i.e.

$$\eta = \frac{\textit{Energy developed by the steam cycle } (W_{cycle})}{\textit{Fuel Energy } (Q_{Coal})} \tag{7}$$

$$\textit{Fuel Energy } (Q_{Coal}) = \textit{Coal Consumption x GCV of coal} \tag{8}$$

$$\textit{Energy Developed by the steam cycle } (W_{cycle}) = W_{HPT} + W_{IPT} + W_{LPT} - W_{CEP} - W_{BFP} \tag{9}$$

The case study power plant fuel energy efficiency was calculated as 36.09%. It is to be noted that worldwide coal power plant efficiency is averaged at 35.1% based on annual coal consumption to annual electricity supply [7].

3. Power Plant with Carbonation Process (CCS Technology)

Existing pulverized coal (PC) power plant is equipped with three units, boiler block, generator block and flue gas clean up block. The carbonation system can be incorporated in the existing power plant just in the line of flue gas clean up block with the flue stack which is typically the last of the hazardous emission reduction systems prior to the stack. As indicated by Prigiobbe *et al.* [8], carbonation process achieves faster reaction rates with higher concentrations of CO_2. Therefore placement of carbonation unit after the existing hazardous emission removal systems would most likely increase the efficiency of the carbonation system. Figure 3 shows a diagram of coal fired power plant with carbonation plant (CCS Technology) which can be applied to a power plant to capture CO_2 from the flue gas. Dotted line of this diagram indicates the system boundaries of carbonation process which includes several pieces of equipment. The simplified diagram of the

carbonation plant is shown in Figure 4, where at fast feed stock is grounded into a specific particle size in a grinder and mixed with water to form slurry, then it is pumped by a feed pump to the reactor pressure. Subsequently, this slurry is heated by a heat exchanger. CO_2 emitted from power plant is passed into the carbonation plant through a compressor. Before carbonation, this compressed CO_2 and feed stock slurry is entered into the carbonation reactor through a heater where reactants are heated to the reaction temperature. After carbonation, non-reacted materials and the products slurry is cooled by a heat exchanger and a cooler and then separated by a filter [3]

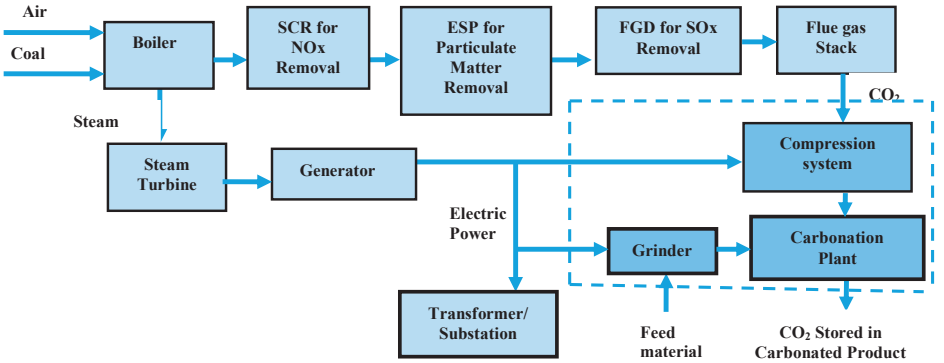

Fig. 3. Coal Fired Power plant with CO_2 capture process (carbonation process)

The sensible heat energy (Q) of the inlet and outlet materials of different stages of carbonation plant at specific temperatures throughout the models was calculated thermodynamics equation $\boldsymbol{Q = mC_pT}$, where m is the mass flow rate in kg/sec, T is the temperature in ^oK and C_p is the specific heat capacity in kJ/kg K which is a function of temperature. Then the models have been run with the carbonation temperatures ranging from 323.15 °K (50°C) up to the maximum carbonation temperature of 523.15°K (250°C). The exothermic gain from carbonation reaction of $CaCO_3$ is 87 kJ/mole [1]. Total exothermic energy was calculated based on the mass flow of carbonation product.

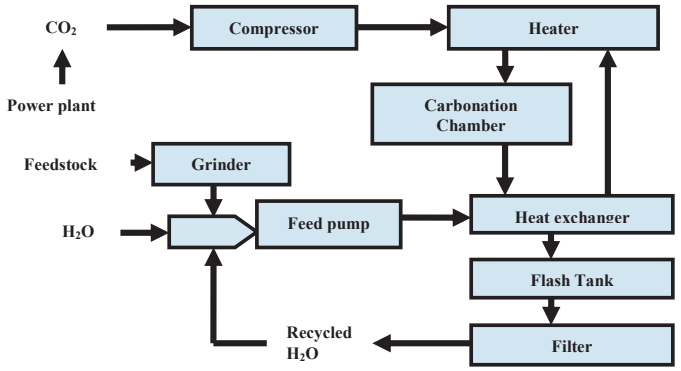

Fig. 4. Simplified diagram of carbonation plant

On completion of the energy balance model of carbonation plant, the model was integrated with case study power plant using Matlab software. Then the impact of the carbonation system on the existing plant's operating efficiency was analyzed. The recoverable heat energy from carbonation plant which includes exothermic heat and product sensible heat are fed into the existing power plant (Figure 5). Electric energy needed to supply to the carbonation plant was added with the existing power plant model as it was mentioned earlier that required electric energy can be supplied from same power plant producing CO_2 emission. Electric energy required for carbonation plant was subtracted from the existing power plant's output capacity. Subsequently, the plant operating efficiency was determined with carbonation process without capturing any heat energy from carbonation plant and then, by adjusting recoverable heat energy from carbonation plant.

4. Result And Discussion

4.1. Efficiency:

Integration of CCS technology in power plant could reduce CO_2 emissions to the atmosphere by about 80% - 90% when compared to a plant without CCS technology, however, capturing CO_2 through CCS technology may increase the fuel cost by 10% to 55% to retain the existing plant output with CCS technology [4]. It was found from literature that CO_2 capture by monoethanol amine (MEA) based absorption technology requires 4 MJ/kg energy to capture CO_2 [4]. The carbonation process requires additional electric energy for compression and grinding and heat energy for heating the reactants before carbonation. Required heat energy can be recovered after one cycle of carbonation process (if energy recovery option is available). But high grade electric energy is required to supply from existing power plant to drive the mineral carbonation process which will reduce the actual capacity of the power plant. To maintain the plant existing capacity, coal input must be increased, that would decrease the overall plant efficiency. The impact of carbonation technology on the power plant efficiency was determined at the different allowable carbonation temperatures (50 ^{o}C to 250 ^{o}C).

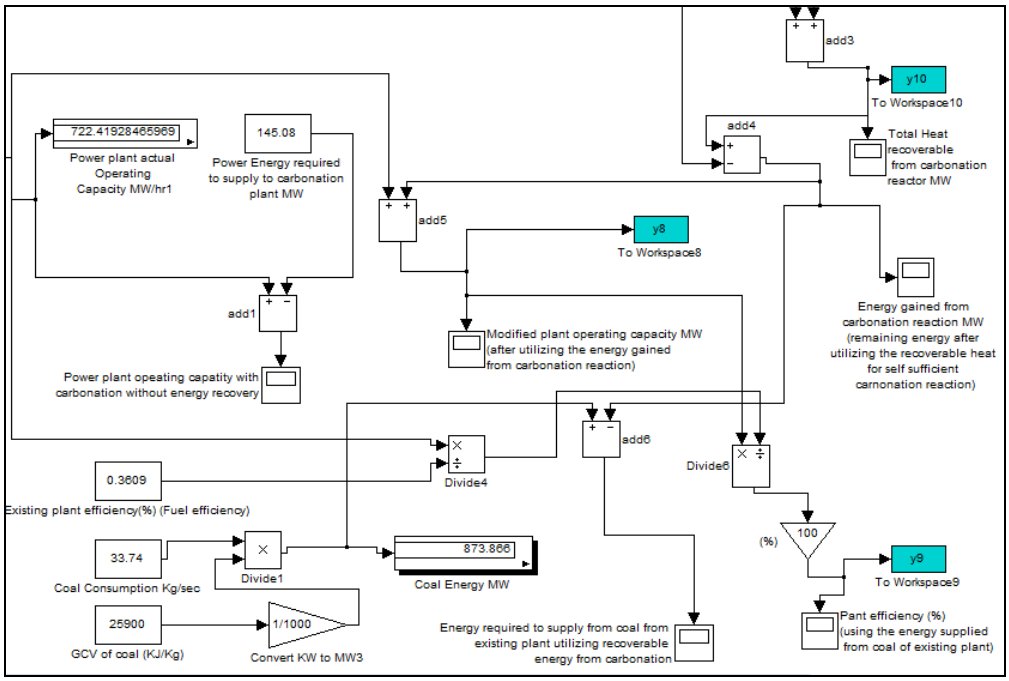

Fig. 5. Integration of carbonation process with power plant in Matlab block diagram

Figure 6 shows the plant efficiency with and without carbonation system. The efficiency was calculated based on recovery option of heat from exothermic reaction and from carbonated product. It can be seen from the Figure 6 that after integration of this process power plant efficiency is reduced from the existing efficiency. The plant efficiency decreased with increases carbonation temperatures. Plant efficiency with wollastonite feed stocks is dropped to 17% without capturing any energy (Figure 6), whereas, if 100% exothermic energy is recovered, plant efficiency rises to 22% at minimum carbonation temperature. At a hypothetical recovery rate of 100% from carbonation product's sensible energy, power plant's operating efficiency can be raised to 33.5% at minimum temperature (50^{o}C). It was assumed in this study that, 100% exothermic gain can be recovered from the carbonation system, however, recoverable sensible heat from products was considered to be between 10% and 100%.

4.2. Realizable Recovery of Product Sensible Heat:

Realizable recovery of sensible heat from carbonation product was considered to be between 10% and 100% of theoretical recoverable sensible heat from product. Figure 7 shows realizable recovery of product sensible heat. It is worth noting that, the most advanced application of carbonated product (carbonates of Ca and Mg) is the use as a substance for thermal energy storage device. Thermal energy storage (TES) is a reservoir of temporary storage of thermal energy at high

or low temperatures which includes sensible heat storage (SHS), latent heat storage (LHS) or bond energy storage (BES) device for later use. These storage devices provide improved performance of energy systems by supplying energy smoothly. SHS is storage system where sensible heat energy is stored or extracted by heating or cooling a liquid or a solid substance without phase change. Different type of substances are used in TES device, which includes, water, heat transfer oils, inorganic molten salts as liquid substance, and rocks, refractory, pebbles as solid substance [8]. Carbonates of Ca and Mg are new candidates for TES device which is useful to supply the demanded energy to power plant. The storage capacity of sensible heat of a TES reservoir with a solid or liquid storage substance can be calculated by the following equation [9],

$$Q\,\mathrm{s} = mc\Delta T = V\rho c\Delta T \tag{9}$$

Where, m is mass of storage substance (kg), V is volume of storage substance (m^3), c is specific heat (kJ/kgK), ρ is density (kg/m^3), and ΔT = temperature difference (K).

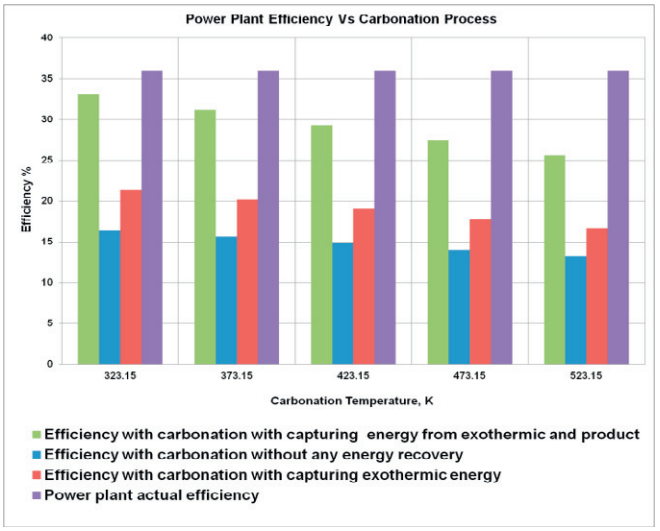

Fig. 6. Power plant efficiency vs carbonation process using wollastonite feed stock

It was stated by Zevenhoven et. al. [10] that carbonate takes the reverse reaction (given below) with H_2O in TES device and release energy. Ca carbonates and Mg carbonates are stable in rainwater and acid solutions and Mg carbonates is stable up to 300°C temperature and Ca carbonate is stable above 800°C [10].

Mg-carbonate + water <--> hydrocarbonate + heat
Calcium carbonate + water <--> hydrocarbonate + heat

4.3. Effect of carbonation process on the existing power output of the power plant:

CO_2 capture processes through carbonation requires significant amount of energy, which reduces the power generation efficiency to 17% from actual efficiency 36.1%, and the net power output is reduced by 63.43% for wollastonite carbonation from existing power output of 315.36 MW which are stated in Figure 8. Due to this, large amount of extra coal is needed to supply to retain the existing plant power output. However, power plant fuel energy consumption, in other word fuel consumption can be reduced from existing fuel consumption by capturing energy from carbonation plant which is shown in Figure 9.

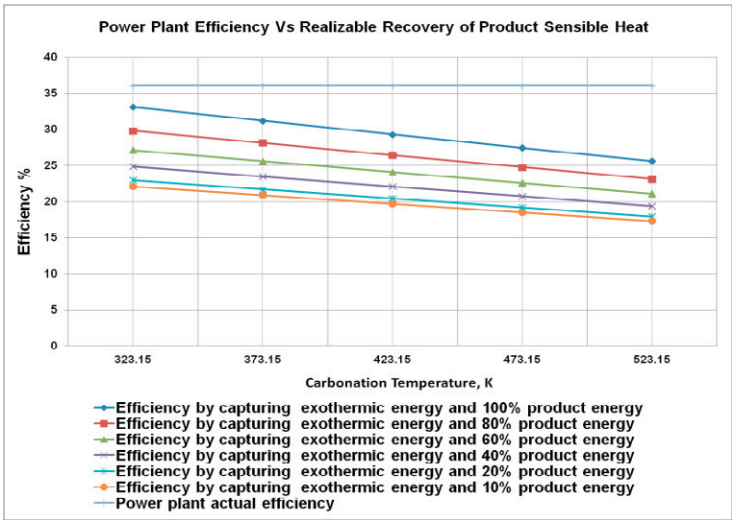

Fig. 7. Realizable Recovery of Product Sensible Heat and plant efficiency (Wollastonite)

4.4. Reduction of CO_2 emission from power plant through Carbonation Process:

It was assumed for this modelling that 100% CO_2 emitted from power plant is passed into the carbonation plant. 100% CO_2 and 65% wollastonite are converted into carbonated product as conversion efficiency of wollastonite is 65%. As coal is the main contributor of CO_2 emission so less coal consumption produce less CO_2 emission. It was observed from this study that less amount of CO_2 is produced if coal consumption is reduced by replacing surplus energy from carbonation process. Figure 10 illustrates emission vs. efficiency of power plant.

5. Conclusions

Feasibility of integration of carbonation system with existing power plant is investigated and discussed in this paper using thermodynamic energy flow model for wollastonite feed stock. Carbonation temperature range of 50^{o}C to 250^{o}C was considered in this investigation. The CO_2 emission is reduced if carbonation system is implemented with power plant, though the power generation efficiency is reduced due to the large amount of extra fuel supply.

Existing power plant efficiency was found to be 36%. If carbonation system is introduced, the plant efficiency reduces to 17%. However, a significant amount of heat energy can be recovered from exothermic reaction of carbonation and carbonated products. At 50^{o}C plant efficiency would be about 22% if only the heat energy from exothermic reaction can be recovered and that would be 33% if all the heat energy from both exothermic reaction and 100% of the sensible heat of carbonated products can be recovered. The plant efficiency slightly decreases with the increase in carbonation temperature. It was found that when all heat energy is recovered, the plant efficiency become 26% at carbonation temperature of 250 ^{o}C, whereas, it is 33% at 50^{o}C. Considering realizable recovery of sensible heat from carbonation product, the theoretical efficiency was found to be about 22%, 24%, 25%, 27% and 30% using 10%, 20%, 40%, 60% and 80% recovery of sensible heat from product at carbonation temperature of 50^{o}C, whereas the efficiency was 33% using 100% recovery of sensible heat from product. Authors are aware that 100% heat energy from exothermic reaction and product could not be recovered in reality. These should be taken into account when carbonation system is implemented with power plant.

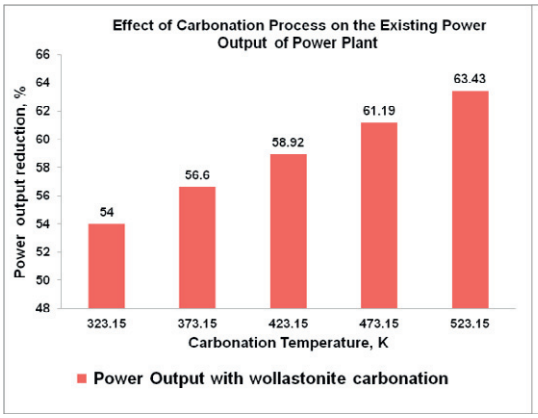

Fig. 8

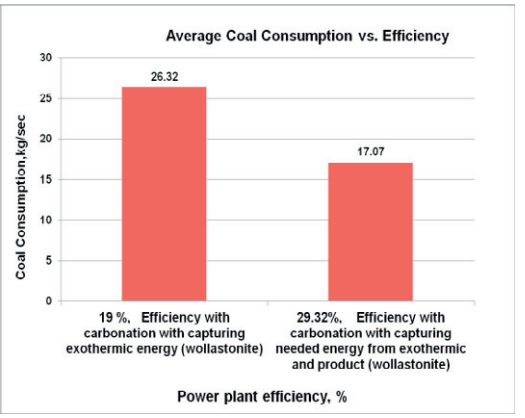

Fig. 9

Fig. 8. Power output reduction percentage with carbonation process
Fig. 9. Average coal consumption capturing energy from carbonation plant

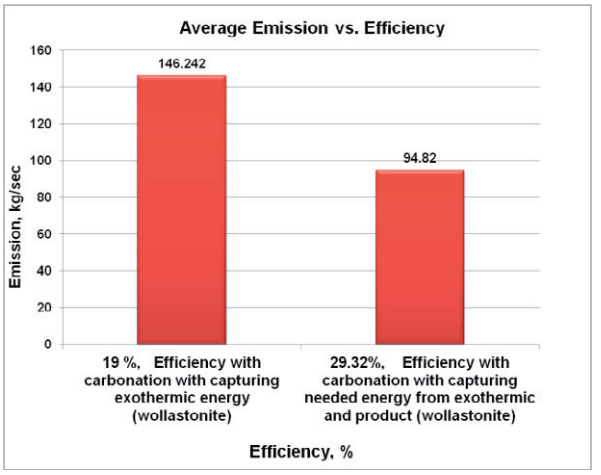

Fig. 10. Average emission capturing energy from carbonation plant

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